

# Energy dependence of $\bar{p}/p$ ratio in $p+p$ collisions

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We have compiled the experimentally measured  $\bar{p}/p$  ratio at midrapidity in  $p+p$  collisions from  $\sqrt{s} = 23$  to 7000 GeV and compared it to various mechanisms of baryon production as implemented in PYTHIA, PHOJET and HIJING/B- $\bar{B}$  models. For the models studied with default settings, PHOJET has the best agreement with the measurements, PYTHIA gives a higher value for  $\sqrt{s} < 200$  GeV and the ratios from HIJING/B- $\bar{B}$  are consistently lower for all the  $\sqrt{s}$  studied. Comparison of the data to different mechanisms of baryon production as implemented in PYTHIA shows that through a suitable tuning of the suppression of diquark-antidiquark pair production in the color field relative to quark-antiquark production and allowing the diquarks to split according to the popcorn scheme gives a fairly reasonable description of the measured  $\bar{p}/p$  ratio for  $\sqrt{s} < 200$  GeV. Comparison of the beam energy dependence of the  $\bar{p}/p$  ratio in  $p+p$  and nucleus-nucleus (A+A) collisions at midrapidity shows that the baryon production is significantly more for A+A collisions relative to  $p+p$  collisions for  $\sqrt{s} < 200$  GeV. We also carry out a phenomenological fit to the  $y_{\text{beam}}$  dependence of the  $\bar{p}/p$  ratio.

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Protons ( $p$ ) and anti-protons ( $\bar{p}$ ) are the most abundantly produced baryons in high energy collisions. These have been measured at various center of mass energies ( $\sqrt{s}$ ) in hadron-hadron [1, 2] and nucleus-nucleus collisions [3] as a function of rapidity ( $y$ ) and transverse momentum ( $p_T$ ). Rapidity dependence of baryon production is expected to provide information on baryon transport and stopping [4] and the  $p_T$  dependence of the yields is expected to help in understanding the baryon production mechanism [2]. The  $\bar{p}/p$  ratio within the assumption of a thermal model is used to obtain the baryon chemical potential in heavy-ion collisions [5, 6]. Recently it has been argued based on QCD that there are constraints on allowing quarks to trace the baryon number [7], although they carry a baryon number of  $1/3$  based on quark model classification. It is argued that the trace of the baryon number could be associated with non-perturbative configurations of gluon fields rather than to valence quarks. All these make the study of the energy dependence of  $\bar{p}/p$  ratio important in high energy collisions, where the role of the gluonic contributions to particle production is expected to increase with  $\sqrt{s}$ .

In the string picture the process of baryon production is not unique. Mesons in such a picture can be viewed with a short string between a quark and anti-quark endpoints. However for the baryons consisting of three quarks it is difficult to visualize in a simple way. Baryon production in string picture is implemented in the PYTHIA model [8]. The simplest mechanism of baryon production in such a picture is through a diquark model. Any quark of a given flavor is assumed to be represented either by a

quark or an antiquark in a color triplet state. Then the baryon and antibaryon are produced as nearest neighbors along the string. Such a model has to deal with the relative probability to pick a diquark over a quark. The extra suppression associated with a diquark containing a strange quark purely from phase space considerations and when a baryon is formed by joining a diquark and a quark, it has to be a symmetric three-quark state. Another equivalent mechanism is that in which diquarks as such are never produced, but baryons appear due to the successive production of several quark-antiquark pairs. Such a mechanism is referred to as the *popcorn* mechanism. These pairs exist by means of the color fluctuations in the field [9]. An advanced version of the popcorn mechanism is described in Ref. [10]. While the simpler popcorn mechanism admits at most one intermediate meson formation, the advanced version, on the other hand, allows for the possibility of many such mesons.

Another model of particle production which is widely used for comparison to data is the PHOJET [11]. The PHOJET, is a two component model that combines the ideas of the Dual Parton Model (DPM) [12] (soft processes) with perturbative QCD (hard processes). The mechanism of Pomeron exchange is at the heart of the DPM. According to the DPM, the leading contribution to multiparticle production in high-energy hadron-hadron collisions arises from the exchange of a single Pomeron between the colliding hadrons. Secondary Pomeron exchanges account for the remaining activity in the event. Each exchanged Pomeron gives rise to two color-neutral chains stretching between quarks and diquarks, for baryons, or quarks and anti-quarks for

mesons. The basic difference between PYTHIA and PHOJET lies in their approach towards an event formation. The starting point of particle production in PYTHIA is through the description of possible hard interactions in  $e^+ + e^-$ ,  $p+p(\bar{p})$  or  $e+p$  colliders and then combines several ideas for the soft hadronic interactions, whereas in PHOJET model it initializes the event generation by describing the soft component of hadron-hadron, photon-hadron or photon-photon interactions at high energies. The hard component is introduced later and calculated by perturbative QCD at the partonic level.

A novel mechanism of baryon transport motivated by the Regge theory [13] and differing from the diquark breaking model has been implemented in the form of an event generator, the HIJING/B- $\bar{B}$  [14]. As discussed briefly earlier, the mechanism is motivated from the non-perturbative gluon field configuration called the baryon junction. The baryon junction is found to be originating from the basic concepts of QCD and is a vertex where the color flux lines flowing from the three valence quarks are connected. The junction is expected to play a dynamical role through the Regge exchange of junction states in high energy collisions. The junction exchange could provide a natural mechanism for the transport of baryon number into the central rapidity region. Further details can be found in Ref. [7, 14]

In this article we compare the energy dependence of the experimentally measured  $\bar{p}/p$  ratio at midrapidity in  $p+p$  collisions for various  $\sqrt{s}$  to the above discussed models. The data for the  $\sqrt{s} = 23, 31, 45, 53$  and  $63$  GeV are from the ISR experiments [1]. The  $\bar{p}/p$  ratio at  $\sqrt{s} = 200$  GeV is from the STAR experiment at RHIC [6]. And the  $\bar{p}/p$  ratio at the highest energies of  $900$  GeV and  $7$  TeV are from ALICE at LHC [2].

Figure 1 shows the  $\bar{p}/p$  ratio at midrapidity for various  $\sqrt{s}$  (except  $\sqrt{s} = 63$  GeV, reasons for not showing these are discussed later), in  $p+p$  collisions as a function of  $p_T$ . All data points are only shown for the  $p_T < 1$  GeV/c. We observe that the ratios are constant as a function of  $p_T$  for each  $\sqrt{s}$  and the value of the  $\bar{p}/p$  ratio increases with  $\sqrt{s}$ . The solid lines show the recent measurements by the ALICE experiment at LHC [2]. The low  $p_T$  dependence of the  $\bar{p}/p$  ratio is discussed in Ref. [2], where a drop of  $\bar{p}/p$  with increase in  $p_T$  is expected in HIJING/B- $\bar{B}$ . In the this paper we discuss only the energy dependence of the  $\bar{p}/p$  ratio at midrapidity by comparison to various models of baryon production.

We first compare the experimental measurements to PYTHIA, PHOJET and HIJING/B- $\bar{B}$  models, then compare the  $\bar{p}/p$  ratio to various baryon production mechanism as implemented in PYTHIA. This is followed by the discussion of asymmetry in proton and anti-proton production and comparison

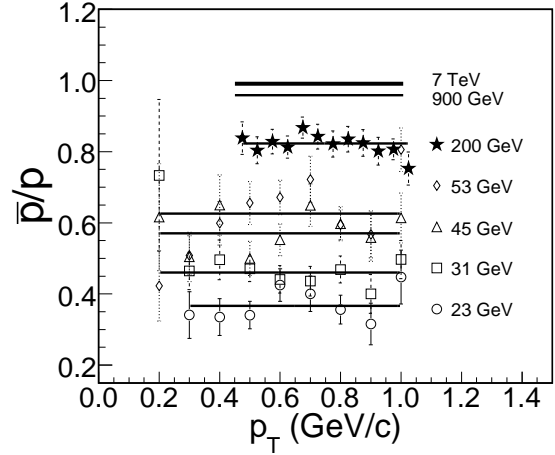


FIG. 1:  $\bar{p}/p$  ratio at midrapidity as a function of  $p_T$  for  $p+p$  collisions. The solid lines corresponds to new data from ALICE at LHC [2]. The  $\bar{p}/p$  ratio for  $\sqrt{s} = 200$  GeV is from the STAR experiment at RHIC [6]. The data for  $\sqrt{s} < 200$  GeV are from the ISR [1]. The dashed lines are straight line fits to the  $p_T$  dependence of the  $\bar{p}/p$  ratios at various  $\sqrt{s}$ , assuming the ratios do not depend on  $p_T$  for the measured range.

to corresponding available results from heavy-ion collisions.

Figure 2 shows the increase of the  $p_T$  integrated  $\bar{p}/p$  ratio at midrapidity with increase in  $\sqrt{s}$  for  $p+p$  collisions. The experimental data are compared to three models, viz, PYTHIA (Ver. 6.4), PHOJET (Ver. 1.12) and HIJING/B- $\bar{B}$  (Ver. 1.34), all with default settings. The  $\bar{p}/p$  ratio for  $\sqrt{s} = 63$  GeV shows an abnormally high value, although shown in the figure, we would not consider it for physics discussions. It is expected that RHIC data collected in the year 2005 at  $\sqrt{s} = 63$  GeV will help in resolving the abnormality in the  $\bar{p}/p$  ratio. All models studied show that the  $\bar{p}/p$  ratio increases with  $\sqrt{s}$  and approaches unity for higher energies (LHC). Infact, the PYTHIA and PHOJET models give very similar values at the LHC energies, while HIJING/B- $\bar{B}$  under predicts the  $\bar{p}/p$  ratio. The major difference occurs for  $\sqrt{s} < 200$  GeV, PYTHIA model gives higher values and HIJING/B- $\bar{B}$  continues to give lower values of  $\bar{p}/p$  ratio. Only the PHOJET model with default settings gives a reasonable description of the  $\sqrt{s}$  dependence of the measured  $\bar{p}/p$  ratio for  $p+p$  collisions.

The PYTHIA model has some variations in the baryon production mechanism. In Fig. 3 we compare the experimental  $\bar{p}/p$  ratio to such variations as implemented in the model. The parameter that we varied is known as MSTJ(12), it can take up values from 0 to 5, with the value of 2 as the default setting

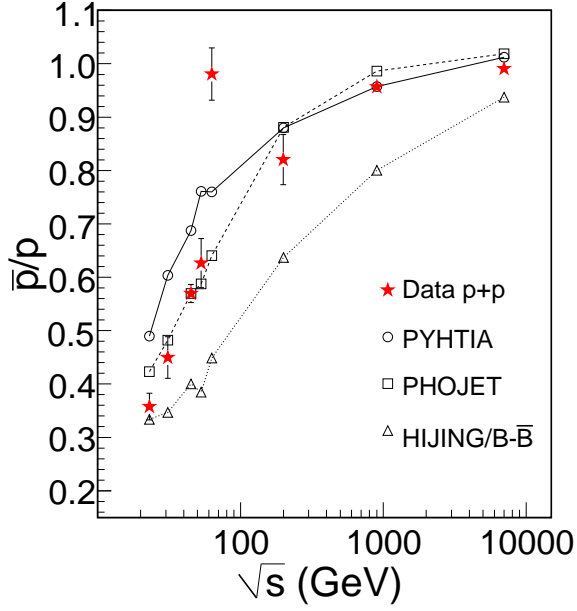


FIG. 2: (Color online)  $\bar{p}/p$  ratio at midrapidity as a function of  $\sqrt{s}$  for  $p+p$  collisions. The experimental data are compared to model calculations from PYTHIA [8], PHOJET [11] and HIJING/B- $\bar{B}$  [14] with default settings.

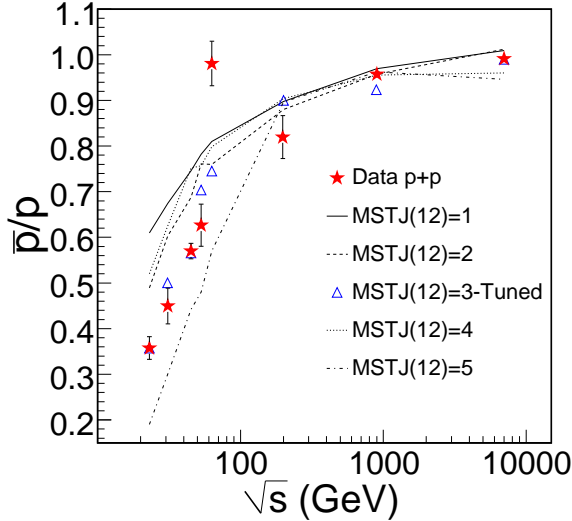


FIG. 3: (Color online)  $\bar{p}/p$  ratio at midrapidity as a function of  $\sqrt{s}$  for  $p+p$  collisions compared to various implementation of the baryon production schemes in PYTHIA. See text for more details.

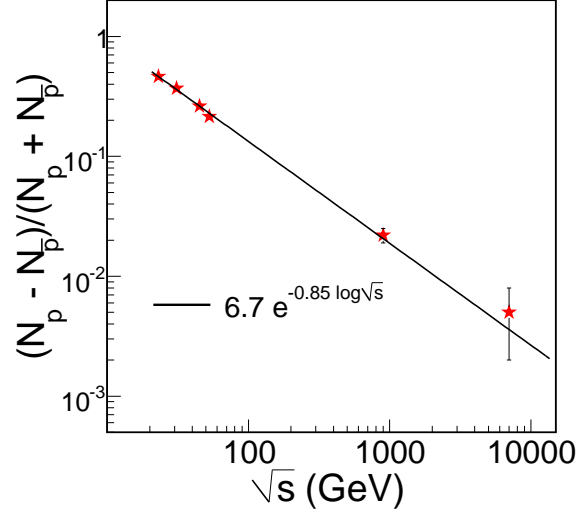


FIG. 4: (Color online) Asymmetry for proton and anti-proton production at midrapidity for  $p+p$  collisions as a function of  $\sqrt{s}$ . The solid line is a fit to the data, with the functional form shown.

(one used in Fig 2). We did not consider MSTJ(12) = 0, as it corresponds to no baryon-antibaryon pair production. The condition MSTJ(12) = 1 refers to the mechanism where baryon production is through diquark-antidiquark pair production with the diquark being treated as a unit. While MSTJ(12) = 2 has the additional possibility for diquark to be split according to the popcorn scheme. The mechanism of baryon production for the case MSTJ(12) = 3 is same as that for MSTJ(12) = 2, but has an additional condition that the production of first rank baryons may be suppressed. For this case, we additionally changed the value of the parameter which governs the suppression of diquark-antidiquark pair production in the color field, compared with quark-antiquark production. The value we put in for this parameter is 0.05 compared to the default value of 0.1. This is referred to as MSTJ(12)=3-Tuned in the Fig. 3. The condition MSTJ(12) = 4 again revolves around MSTJ(12) = 2 with an extra condition that the diquark vertices are suppressed. The last scheme implemented corresponds to MSTJ(12)= 5 is similar to MSTJ(12) = 2, but with an advanced version of the popcorn model. Fig. 3 shows that for the lower beam energies the model results with the condition MSTJ(12)=3-Tuned has a reasonable agreement with the experimental data. For higher  $\sqrt{s}$  all the above conditions give similar values of  $\bar{p}/p$  ratio.

Different baryon production mechanisms could lead to an asymmetry in the production of protons

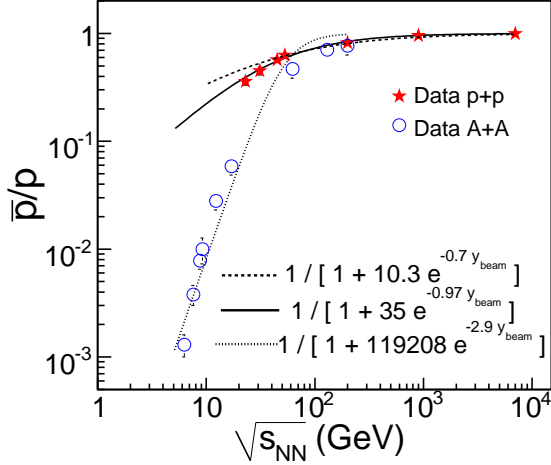


FIG. 5: (Color online) Comparison of beam energy of  $\bar{p}/p$  ratio at midrapidity for  $p+p$  and nucleus-nucleus (A+A) collisions. The solid, dash and dotted lines are fits to the  $p+p$  and A+A data inspired by the model based on baryon string junction picture [7, 18].

and anti-protons. This asymmetry can be measured by constructing the following ratio,

$$\frac{N_p - N_{\bar{p}}}{N_p + N_{\bar{p}}}, \quad (1)$$

where  $N_p$  and  $N_{\bar{p}}$  are the number of protons and anti-protons. As pair production would lead to same number of protons and anti-protons, the asymmetry will have a value of zero. Any non-zero value indicates the fraction of protons in midrapidity due to effects such as stopping. Figure 4 shows the asymmetry ratio for protons and anti-protons as measured in  $p+p$  collisions for various  $\sqrt{s}$  ranging from 23 GeV to 7 TeV. The asymmetry is found to decrease with increase in  $\sqrt{s}$ , indicating the decreasing contributions of protons due to stopping at midrapidity. The ratio changes from about 46% at  $\sqrt{s} = 23$  GeV to 0.5% at the top LHC energy of 7 TeV. This range in  $\sqrt{s}$  corresponds to a range in  $y_{\text{beam}}$  of 3 to 9 units, respectively. This information is useful to study double baryon production in  $p+p$  collisions [7] and baryon number flow over long rapidity interval [15]. The solid line in Fig. 4 is a fit ( $\chi^2/ndf = 3/4$ ) to the experimental data with the function  $Ae^{-B \log \sqrt{s}}$ , with the parameters  $A = 6.7 \pm 0.9$  and  $B = 0.85 \pm 0.04$ .

In Fig. 5 we compare the beam energy dependence of the experimentally measured midrapidity  $\bar{p}/p$  ratio in  $p+p$  collisions to the available  $\bar{p}/p$  ratios at midrapidity in nucleus-nucleus (A+A) collisions. The A+A collision data are taken from the experiments at AGS [16], SPS [17] and RHIC [3]. For both the systems the  $\bar{p}/p$  rapidly rises with beam

energy and approaches unity. For the  $p+p$  collisions the  $\bar{p}/p$  ratio has a value of  $0.991 \pm 0.005(\text{stat.}) \pm 0.014(\text{syst.})$  at 7 TeV, while for heavy-ion collisions the  $\bar{p}/p$  ratio has a value of  $0.77 \pm 0.14$  at 200 GeV. Looking at the region in beam energy where there is overlap between  $p+p$  and A+A collisions, the relative proton contributions at midrapidity for A+A collisions is more than for  $p+p$  collisions. The values of the ratio seem to become equal around 200 GeV. Also shown in the figure are fits to the experimental  $\bar{p}/p$  ratio in the  $p+p$  collisions to a function of the form  $[1 + C \exp[(\alpha_J - \alpha_P)y_{\text{beam}}]]^{-1}$ . The dashed line corresponds to  $\alpha_J - \alpha_P = (1.2 - 0.5) = -0.7$ , values as expected from a Regge model where the baryon pair production at very high energy is governed by Pomeron exchange and baryon transport by string-junction exchange [7, 18]. The  $\alpha_J$  and  $\alpha_P$  parameters corresponds to the junction intercept and the Pomeron intercept in the models. The  $\chi^2/ndf$  for the fit is 66/6. The best fit ( $\chi^2/ndf = 4/5$ ) is however obtained for  $\alpha_J - \alpha_P = -0.97 \pm 0.05$  (solid line), with about a factor of 3 increase in the value of parameter  $C$  compared to the results presented in dashed lines. The value of  $C$  for the case is  $10.3 \pm 0.4$  and that for the second case (solid line) is  $35 \pm 7$ . The Regge model inspired fit to the heavy-ion data (dotted line), yields a poor  $\chi^2/ndf = 33/7$ , with fit parameters  $C = 119208 \pm 49600$  and  $\alpha_J - \alpha_P = -2.9 \pm 0.2$ . The fit misses the the higher energy data points where such a model is more reliable. Constraining the fit to the energy range of 23 to 200 GeV gives  $C = 205 \pm 580$  and  $\alpha_J - \alpha_P = -1.2 \pm 0.6$  with  $\chi^2/ndf = 0.6/1$ . Upcoming heavy-ion data at higher beam energies in LHC will give a clear picture of applicability of such a model to heavy-ion collisions.

In summary, we have presented a compilation of the available data for  $\bar{p}/p$  ratio at midrapidity for  $p+p$  collisions as a function of  $\sqrt{s}$ . We have also compared these ratios to the beam energy dependence from heavy-ion collisions and found that below  $\sqrt{s_{\text{NN}}} = 200$  GeV, the proton contribution at midrapidity in A+A collisions is significantly more compared to those in  $p+p$  collisions. The  $\bar{p}/p$  ratio is constant as a function of  $p_T$  for all the beam energies for  $p_T < 1$  GeV/c. This experimental observation already puts a constrain on mechanism of baryon production such as those implemented in HIJING/B-B. We also compared the  $\bar{p}/p$  ratio vs.  $\sqrt{s}$  to results from various models with different baryon production mechanisms, such as PYTHIA, PHOJET and HIJING/B-B with default settings. It is observed that PHOJET gives the best description of the data for all  $\sqrt{s}$ , PYTHIA gives higher values of the  $\bar{p}/p$  ratio for  $\sqrt{s} < 200$  GeV and HIJING/B-B under predicts the ratio for all beam energies. A detailed investigation of various mechanisms of baryon pro-

duction as implemented in PYTHIA shows that the baryon production through diquark-antidiquark pair production with the diquark being treated as a unit and the additional possibilities (arrived by tuning various parameters) of diquark splitting according to the popcorn scheme and the production of first rank baryons suppressed gives a reasonable description for the  $\bar{p}/p$  ratio for  $\sqrt{s} < 200$  GeV. The asymmetry, a measure of proton stopping at the midrapidity in  $p+p$  collisions are presented. The fraction of protons stopped around midrapidity varies from 46% at  $\sqrt{s} = 23$  GeV to 0.05% for  $\sqrt{s} = 7$  TeV. This energy range corresponds to a range in  $y_{\text{beam}}$  from 3 to 9 units, respectively. The data has also been compared to baryon string junction moti-

vated phenomenological function whose parameters can constrain the Regge-model inspired descriptions of baryon asymmetry in  $p+p$  collisions.

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- [1] British-Scandinavian Collaboration, B. Alper *et al.*, Nucl. Phys. B 100, 237 (1975).
  - [2] ALICE Collaboration, K. Aamodt *et al.*, arXiv:1006.5432.
  - [3] STAR Collaboration, B.I. Abelev *et al.*, Phys. Rev. C 81, 024911 (2010) and the references therein.
  - [4] BRAHMS Collaboration, I. G. Bearden *et al.*, Phys. Rev. Lett. 93, 102301 (2004).
  - [5] J. Cleymans and K. Redlich, Phys. Rev. C 60, 054908 (1999); A. Andronic, P. Braun-Munzinger and J. Stachel, Nucl. Phys. A 772, 167 (2006).
  - [6] STAR Collaboration, B.I. Abelev *et al.*, Phys. Rev. C 79, 034909 (2009).
  - [7] D. Kharzeev, Phys. Lett. B 378, 238 (1996) and the reference therein.
  - [8] T. Sjostrand, *et al.*, Computer Physics Commun. 135, 238 (2001); T. Sjostrand and M. van Zijl, Phys. Rev. D 36, 2019 (1987); T. Sjostrand and P. Skands, Eur. Phys. J. C 39, 129 (2005); T. Sjostrand and P. Skands, JHEP 0605, 026 (2006).
  - [9] B. Andersson, G. Gustafson and T. Sjostrand, Physica Scripta 32, 574 (1985).
  - [10] P. Eden and G. Gustafson, Z. Phys. C 75, 41 (1997); P. Eden, hep-ph/9610246.
  - [11] R. Engel, Z. Phys. C 66, 203 (1995); R. Engel, J. Ranft and S. Roesler, Phys. Rev. D 52, 1459 (1995).
  - [12] A. Capella *et al.*, Phys. Lett. 81B(1), 68 (1979); A. Capella and J. T. T. Van, Phys. Lett. 93B(1,2), 146 (1980); A. Capella and J. T. T. Van, Z. Phys. C 10, 249 (1981); A. Capella *et al.* Phys. Rep. 236(4,5), 225 (1994).
  - [13] G.C. Rossi, G. Veneziano, Nucl. Phys. B 123, 507 (1977); Phys. Rep. 63, 153 (1980).
  - [14] S.E. Vance, M. Gyulassy, and X.N. Wang, Phys. Lett. B 443, 45 (1998).
  - [15] Boris Kopeliovich and Bogdan Povh, Phys. Lett. B 446, 321 (1999).
  - [16] E877 Collaboration, J. Barrette *et al.*, Phys. Rev. C 62, 024901 (2000); E802 Collaboration, L. Ahle *et al.*, Phys. Rev. C 60, 064901 (1999).
  - [17] NA49 Collaboration, C. Alt *et al.* Phys. Rev. C 73, 044910 (2006); T. Anticic *et al.*, Phys. Rev. C 69, 024902 (2004).
  - [18] A.B. Kaidalov, L.A. Ponomarev and K.A. Ter-Martirosyan, Sov. J. Nucl. Phys., 44, 468 (1986).